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Search for jet extinction in the inclusive jet-pt spectrum from proton-proton collisions at s√= 8 TeV

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Search for jet extinction in the inclusive jet-p_{T} spectrum from proton-proton collisions at $\sqrt{s} = 8\,\mathrm{TeV}$

The CMS Collaboration*

Abstract

The first search at the LHC for the extinction of QCD jet production is presented, using data collected with the CMS detector corresponding to an integrated luminosity of $10.7\,\mathrm{fb}^{-1}$ of proton-proton collisions at a center-of-mass energy of 8 TeV. The extinction model studied in this analysis is motivated by the search for signatures of strong gravity at the TeV scale (terascale gravity) and assumes the existence of string couplings in the strong-coupling limit. In this limit, the string model predicts the suppression of all high-transverse-momentum standard model processes, including jet production, beyond a certain energy scale. To test this prediction, the measured transverse-momentum spectrum is compared to the theoretical prediction of the standard model. No significant deficit of events is found at high transverse momentum. A 95% confidence level lower limit of 3.3 TeV is set on the extinction mass scale.

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*See Appendix A for the list of collaboration members

1 Introduction

The scattering of high-energy particles in theories of quantum gravity is fundamentally different from that expected by the local quantum field theories of the standard model (SM) [1]. The Planck scale, the threshold at which quantum gravity becomes strong, is therefore a fundamental boundary beyond which some modification to the SM is required. The Planck scale differs from the electroweak scale by 16 orders of magnitude, creating what is commonly known as the hierarchy problem. There are many models that propose a mechanism by which these two scales are related to one another through the hypothesized existence of extra spatial dimensions. Propagation of gravitons through these extra dimensions could explain the relative weakness of gravity compared to the strong and electroweak interactions. Depending on the model, a variety of striking signatures of physics beyond the SM may be observed. As a result, models that predict terascale gravity have been the subject of numerous searches at the CERN LHC [2–11]. Some of these searches are designed to look for effects such as resonant production and decay of new states, e.g. Randall–Sundrum gravitons [12], as well as for continuum enhancements to SM processes from both virtual and direct graviton production [13]. Direct searches for production of microscopic black holes consider events with high transverse momentum (p_{T}) and multiple objects from the decay of possible high-entropy intermediate states [1, 14, 15].

As of yet, no signal indicative of terascale gravity has been found. Nevertheless, it has been suggested that evidence of terascale gravity could also be found through more subtle effects on the jet-p_{T} spectrum manifesting themselves as a deviation from the predictions of quantum chromodynamics (QCD) [1, 14, 16, 17]. While the production of black holes or particles indicative of non-perturbative quantum gravity can have a rapidly increasing total cross section beyond some energy scale, their decay to isolated jets or other low-multiplicity final states could be suppressed, leading to a full suppression of high-p_{T} SM scattering processes (jet extinction). Because jet production is the leading SM process at high p_{T}, such effects would be initially noticeable as a jet extinction signature [17]. In this sense, the search for jet extinction is complementary to searches for black holes in high-multiplicity final states. These final states arise in the asymptotic limit, where black holes are expected to behave classically [15]. The extinction search explores an intermediate regime, where a high-multiplicity signature may not be readily observable.

There are several models that include extinction phenomena [16, 17]. In this, the first search for extinction effects at the LHC, we consider a model with a large-width Veneziano form factor modification of QCD processes with an extinction mass scale M equivalent to the modified Planck scale [17]. This form factor is discussed in greater detail in Section 3. Beyond the scale M, the predominance of intermediate high-entropy string states will suppress high-p_{T} SM jet production. This search exploits techniques developed for the measurement of the differential jet production cross section as a function of p_{T} at the CMS [18] experiment to search for a modification of the jet-p_{T} spectrum consistent with extinction phenomena, in which there are fewer high-p_{T} jets than expected from the SM. This analysis is especially sensitive to the correlations of the systematic uncertainties between bins in jet-p_{T}, so a detailed evaluation of the systematic uncertainties associated with the jet energy scale (JES) and the parton distribution functions (PDFs) is performed.

2 The CMS detector

The central feature of the CMS detector [19] is a superconducting solenoid of 6 m internal diameter, providing a field of 3.8 T. Within the field volume are silicon pixel and strip trackers, a lead-tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL). Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke.

The CMS experiment uses a right-handed coordinate system, with the origin at the nominal interaction point, the x axis pointing to the center of the LHC ring, the y axis pointing up (perpendicular to the plane of the LHC ring), and the z axis along the counterclockwise-beam direction. The polar angle, θ, is measured from the positive z axis and the azimuthal angle, ϕ, is measured in the xy plane. The pseudorapidity is defined as $\eta = -\ln[\tan(\theta/2)]$.

The first level of the CMS trigger system is composed of customized hardware and uses information from the calorimeters and muon detectors to select events of interest within a 4 μs interval following each beam crossing. The high-level trigger [20] (HLT) processor farm further decreases the event rate from about 100 kHz to about 400 Hz before the data are recorded for analysis.

3 Modeling of the SM and extinction hypotheses

The SM prediction for the jet-p_T spectrum is calculated at next-to-leading order (NLO) with the NLOJET++ program within the FASTNLO framework [21–23]. The CT10 PDF set [24] is used in this calculation. The renormalization and factorization scales, μ_R and μ_F, are set equal to the jet-p_T. The NLO jet spectra do not include non-perturbative (NP) effects or any modeling of the detector response. The NP effects, which account for hadronization and multi-parton interactions, are incorporated as corrections determined from the PYTHIA 6.424 [25] Monte Carlo (MC) generator. The generator is used to simulate QCD events with and without NP effects. The corrections are derived from the ratio of the resulting p_T spectra. The NP correction decreases monotonically as a function of jet-p_T, from 1.03 at 592 GeV to 1.01 at 2500 GeV. This process is repeated using the HERWIG 2.4.2 [26] generator. The difference between the corrections derived from these generators is found to be negligible in the phase space of this analysis. The corrected NLO jet spectra are convolved with a function that models the jet energy resolution (JER) in the CMS detector [27]. These smeared spectra can be compared directly to the observed spectrum. The smeared NLO jet spectrum is referred to as $\mathrm{d}\sigma^{\mathrm{QCD}}/\mathrm{d}p_{\mathrm{T,NLO}}$. This procedure is repeated to produce a smeared leading-order (LO) jet-p_T spectrum, labeled as $\mathrm{d}\sigma^{\mathrm{QCD}}/\mathrm{d}p_{\mathrm{T,LO}}$. The predicted spectrum does not include weak radiative corrections [28], but the impact of these corrections on our sensitivity to an extinction signature is evaluated during the limit-setting procedure.

The effects of extinction at LO are also modeled using the PYTHIA MC generator. The matrix elements of each color channel are modified by Veneziano-type form factors [17, 29], which affect all $2 \rightarrow 2$ scattering amplitudes. The input parameters for these form factors are the extinction mass scale M and a dimensionless width parameter related to the strength of the string coupling. For small values of the width parameter, these form factors are similar to those that describe string resonances [29, 30]. This is referred to as the weak-coupling limit. The regime where the width parameter is close to unity is known as the strong-coupling limit. In this limit, extinction physics rapidly overwhelms LO SM processes as well as any resonant string production. Beyond the scale M, scattering processes are dominated by a continuum of high-entropy intermediate states, which results in suppression of SM jet production [17].

This search assumes a width parameter of one, the absolute strong-coupling limit of the string model. Values of the width above one represent a very different phenomenology where the form factors no longer monotonically decrease as a function of jet momentum. This range of the width parameter has not been studied in this analysis.

The effects of extinction are predominantly found in $2 \to 2$ scattering processes. Such processes are dominated by the LO calculation at a given p_{T} scale. The signal is approximated with a LO generator. The extinction process is assumed to have a very weak effect on higher-order interactions. A sigmoid function provides a good functional fit of the effect of the Veneziano form factors on the LO jet-p_{T} spectrum [17]:

$$F(p_{\mathrm{T}}, M) = \frac{1}{1 + \exp \frac{p_{\mathrm{T}} - p_{\mathrm{T},1/2}(M)}{p_{\mathrm{T},0}(M)}}. \tag{1}$$

Here, $p_{\mathrm{T},1/2}$ describes the p_{T} threshold at which LO jet production is reduced to half the SM expectation, while $p_{\mathrm{T},0}$ indicates how quickly the LO cross section exponentially falls relative to the SM prediction. This relation yields the following equation for the jet-p_{T} spectrum assuming extinction at LO, where σ^{Ext} is the jet production cross section assuming extinction:

$$\frac{\mathrm{d}\sigma^{\mathrm{Ext}}}{\mathrm{d}p_{\mathrm{T,LO}}} = \frac{\mathrm{d}\sigma^{\mathrm{QCD}}}{\mathrm{d}p_{\mathrm{T,LO}}} F(p_{\mathrm{T}}, M) \tag{2}$$

and at NLO:

$$\frac{\mathrm{d}\sigma^{\mathrm{Ext}}}{\mathrm{d}p_{\mathrm{T,NLO}}} = \frac{\mathrm{d}\sigma^{\mathrm{QCD}}}{\mathrm{d}p_{\mathrm{T,NLO}}} - \frac{\mathrm{d}\sigma^{\mathrm{QCD}}}{\mathrm{d}p_{\mathrm{T,LO}}} + \frac{\mathrm{d}\sigma^{\mathrm{Ext}}}{\mathrm{d}p_{\mathrm{T,LO}}}. \tag{3}$$

Several simulations of LO jet production are performed, assuming values of M between 2 and 5 TeV in increments of 500 GeV. The jet-p_{T} spectrum is produced at NLO for each sample using NP corrections and resolution smearing as described above. The values of $p_{\mathrm{T},1/2}(M)$ and $p_{\mathrm{T},0}(M)$ are extracted from a fit of $F(p_{\mathrm{T}}, M)$ to the expected p_{T} distribution for each value of M. The intermediate values of $p_{\mathrm{T},1/2}(M)$ and $p_{\mathrm{T},0}(M)$ are interpolated between these fitted points. The fitted value of $p_{\mathrm{T},0}(M)$ is nearly independent of M and ranges between 260 and 330 GeV, while $p_{\mathrm{T},1/2}(M)$ is about half of M. The systematic uncertainty associated with the choice of fit is negligible.

For finite values of M, the predicted jet-p_{T} spectrum is suppressed in systems with an invariant mass above M. At very large values of M, the SM and extinction spectra become identical.

4 Event reconstruction and selection

A particle-flow algorithm [31, 32] is used to reconstruct the events. Jets are formed by clustering the reconstructed particle-flow objects using the anti-k_{T} algorithm [33] with a distance parameter R of 0.7. This value is larger than the usual distance parameter of 0.5 used in most CMS analyses. The larger cluster size reduces the likelihood that jets will be lost because of detector effects. The jet transverse momentum resolution is typically 15% at p_{T} = 10 GeV, 8% at 100 GeV, and 4% at 1 TeV. Jet energy corrections are derived from simulation and are confirmed with measurements of energy balance in recorded dijet and photon+jet events. The combined corrections are approximately 5–10%, depending on the pseudorapidity and p_{T} of the jet. To suppress spurious signals from detector noise [34], jets are required to satisfy stringent selection criteria [35]. Specifically, each jet must contain at least two particles, one of which is a charged hadron. Additionally, each of the jet energy fractions carried by neutral hadrons, photons, electrons, and muons must be less than 90%. This analysis is conducted in a regime where the purity and acceptance of the jets in data are both close to unity, and therefore no systematic uncertainty is attributed to the selection criteria.

The data used in this analysis were collected from an HLT trigger that accepted events containing at least one jet with $p_T > 320\,\mathrm{GeV}$. An offset is applied to trigger-selected jets to subtract the energy deposited as a result of additional interactions per beam crossing (pileup); this offset does not affect the trigger efficiency. Events with objects originating from an interaction within an LHC beam crossing are selected by requiring the presence of at least one primary vertex within 24 cm of the detector center along the z axis. The primary event vertex is chosen from all reconstructed vertices by selecting the one with the largest sum of the p_T^2 of all associated tracks. For the purpose of additional noise suppression, the missing transverse energy, defined as the magnitude of the vector sum p_T of all reconstructed particle-flow objects, must be less than 30% of the total transverse energy deposited in the detector. All jets in each event that pass the selection criteria are binned as a function of jet-p_T, following a convention adopted by other inclusive-jet analyses in CMS. The bin widths are variable, increasing with jet-p_T and corresponding approximately to the jet-p_T resolution [18]. Jets are required to have $p_T > 592\,\mathrm{GeV}$ and pseudorapidity $|\eta| < 1.5$ to ensure that the trigger is at least 99% efficient in all p_T bins used. This search is performed in 18 p_T bins between 592 and 2500 GeV.

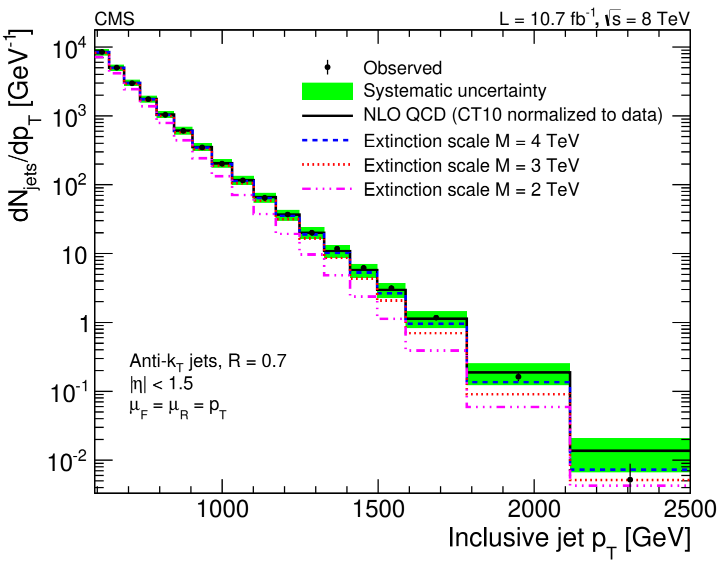

Figure 1: Inclusive jet-p_T spectrum (points) for $|\eta| < 1.5$, as observed in data. The SM NLO simulation with non-perturbative corrections, convolved with the detector response and normalized to the total number of jets observed in data, is shown by the solid line. The spectra predicted by the extinction model are defined relative to the SM prediction as described by Eq. 3 for the values of $M = 2, 3,$ and $4\,\mathrm{TeV}$ and shown by the dashed lines. The colored band shows the magnitude of the sources of systematic uncertainty added in quadrature. These sources include the JES, JER, PDFs, and scale variations. An additional source of systematic uncertainty is attributed to the integrated luminosity during all formal comparisons between the data and models, but has little impact on the sensitivity to an extinction signature. The renormalization scale (μ_R) and factorization scale (μ_F) are set to the p_T of the hard-scattered parton.

A comparison between the observed inclusive jet-p_T spectrum and the spectrum predicted at

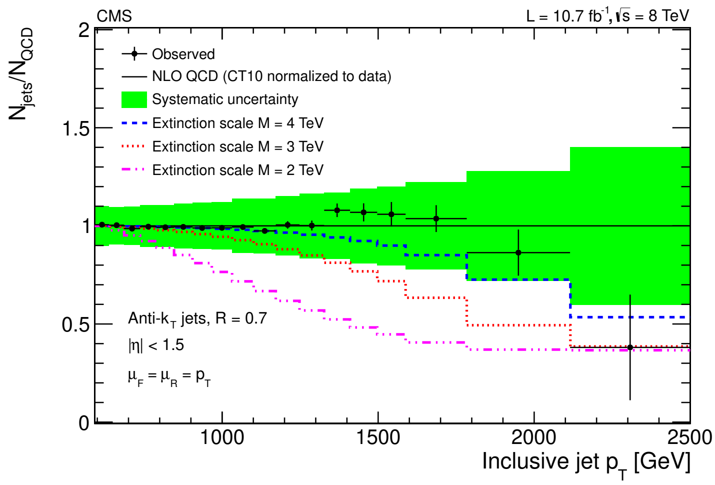

Figure 2: The ratio of the inclusive jet p_T spectrum to the NLO QCD prediction with non-perturbative corrections and convolved with the detector resolution. The horizontal bars on the data indicate the width of each bin in p_T. The colored band shows the quadratic sum of the sources of systematic uncertainty, including JES, JER, PDFs, and scale variations. The uncertainty in the integrated luminosity is excluded, as the model predictions have been normalized to the number of jets observed in data. The dashed lines indicate the effects of extinction at three different values of the extinction mass scale, $M = 2$, 3, and 4 TeV.

NLO with the CT10 PDF set is shown in Figs. 1 and 2. The predicted spectrum includes non-perturbative corrections and smearing by the detector response, and is normalized to the total number of jets in data that pass all selection criteria. However, in the comparison of the model to the data as described in Section 5, the SM distribution is instead normalized to the number of jets expected given an integrated luminosity of 10.7 fb^{-1}. The number of jets observed in data is 3% lower than the number expected assuming the CT10 PDF set at NLO. This discrepancy is attributed to uncertainty in the PDF parameters, scale variations in the cross section calculation, or uncertainty in the total integrated luminosity. As the search for an extinction signature is only concerned with the shape of the jet-p_T spectrum, a small shift in the absolute normalization has little impact on the sensitivity. In Figs. 1 and 2 the data and the extinction model are compared after any differences in the normalization have been resolved. In these figures, the quadratic sum of all sources of systematic uncertainty is shown. The total systematic uncertainty includes contributions from both theoretical and experimental sources. The theoretical uncertainty is composed of the uncertainty from the PDFs as well as the uncertainty obtained by varying the renormalization and factorization scales. The experimental uncertainty is derived from the uncertainties in the JES and JER. During the formal comparison of the model to data where the predicted spectrum is not normalized to the number of jets observed, an additional source of uncertainty is attributed to the integrated luminosity. Figure 2 shows the ratio of the inclusive spectrum to the SM NLO expectation and includes the predicted spectra from the extinction model for three different values of the extinction mass scale M.

5 Statistical method and systematic uncertainties

To distinguish between SM NLO jet production and the alternative hypothesis (jet extinction), a profile-likelihood ratio test statistic [36] is constructed as a function of a signal strength parameter, $\beta \equiv M^{-2}$. The variable β is chosen so that as $\beta \to 0$ the extinction model approaches the SM prediction.

We set limits using the modified-frequentist criterion $\mathrm{CL_s}$ [37, 38]. All sources of systematic uncertainty are treated as nuisance parameters with log-normal prior constraints and are constructed in the likelihood to have the same value across all jet-p_T bins. This construction implicitly assumes that the systematic uncertainties are completely correlated in jet p_T.

To account for correlations in the JES and PDF uncertainties between p_T bins, the uncertainties are subdivided into their underlying components. These individual components are strongly correlated across all p_T bins and tend to be dominant at different values of jet-p_T. As an example, uncertainties in the gluon PDF will be dominant at low p_T compared to uncertainties in the quark PDFs. The JES uncertainty is decomposed into each of its orthogonal sources. For the PDF uncertainty, the contributions from each of the eigenvectors in the CT10 [24] PDF set are evaluated separately. As a crosscheck, the search is repeated with respect to the MSTW2008 [39] PDF set. Among the PDF sets in common use, the CT10 set predicts the highest inclusive jet cross section at high p_T, while the MSTW2008 set gives one of the lowest. The results derived with respect to these two PDF sets serve as bounds on the result expected when using other sets, including those which are used in comparison to dedicated measurements of the inclusive jet production cross section [18], such as NNPDF [40], HERA [41], or ABKM [42].

The CT10 PDF set comprises a central prediction and 26 eigenvectors. The central prediction assumes all PDF input parameters are set to their central values. Each eigenvector pair corresponds to the upward and downward uncertainty in one of those input parameters. The difference between the predictions of each eigenvector pair and the central prediction is taken as a source of systematic uncertainty at $\pm 1\sigma$. A source of systematic uncertainty is defined as non-trivial if, at one standard deviation in either direction, it produces a shift in any p_T bin greater than 1% of the occupancy given by the central prediction. Under this definition, 15 of the 26 CT10 eigenvectors are found to be non-trivial.

The relative uncertainty described by the combined variation of these eigenvector sets in quadrature and the scale variations are shown in Fig. 3 as a function of jet-p_T. The uncertainties associated with the renormalization and factorization scales are computed by varying the scales coherently up and down by a factor of 2. As the effect of extinction on the jet-p_T spectrum is expressed relative to the SM prediction, by construction the PDF variations do not affect any of the extinction parameters.

Given the exponentially falling nature of the inclusive jet-p_T spectrum, the JES is one of the dominant sources of systematic uncertainty. The JES uncertainty is composed of 19 orthogonal sources. Of these, seven are found to be non-trivial according to the criterion defined above: the absolute p_T scale; the single pion response in the ECAL; the single pion response in the HCAL; the flavor composition correction; the time dependence; the pileup p_T scale; and the extrapolation of the absolute scale into the high-p_T regime [27]. The effects of JER are also included as nuisance parameters. The uncertainty in luminosity is taken as a constant scale factor with a 2.6% relative uncertainty [43]. The relative uncertainty of all non-trivial detector-related sources of systematic uncertainty (JES, JER, and integrated luminosity) is shown in Fig. 4 as a function of jet-p_T.

Including systematic uncertainties, the best-fit value of β is $(0.008 \pm 0.033)\,\mathrm{TeV}^{-2}$, which is consistent with the SM expectation.

The dependence of $\mathrm{CL_s}$ on the parameter β is shown in Fig. 5. The observed upper limit on β is $0.090\,\mathrm{TeV}^{-2}$ at 95% confidence level (CL), translating to an observed lower limit on M of 3.3 TeV. The expected upper limit on β is $0.088\,\mathrm{TeV}^{-2}$ at 95% CL, corresponding to an expected lower limit on M of 3.4 TeV. These relatively close expected and observed values reflect good

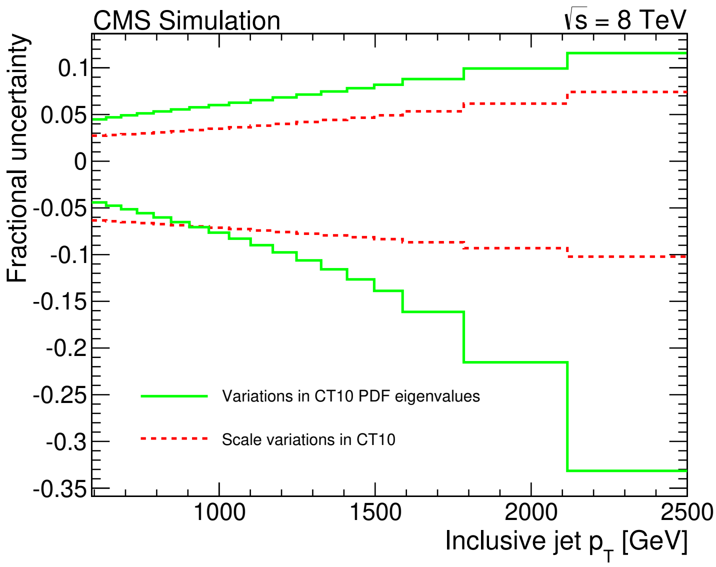

Figure 3: Uncertainty at ± 1 standard deviation described by the combined variations of all CT10 PDF eigenvectors added in quadrature (solid lines), as well as the scale variations (dotted lines). The uncertainty is expressed as a fraction of the central occupancy of each p_T bin. For the fit of the model to data and the limit setting procedure, the PDF uncertainty is subdivided into individual sources for each eigenvector pair.

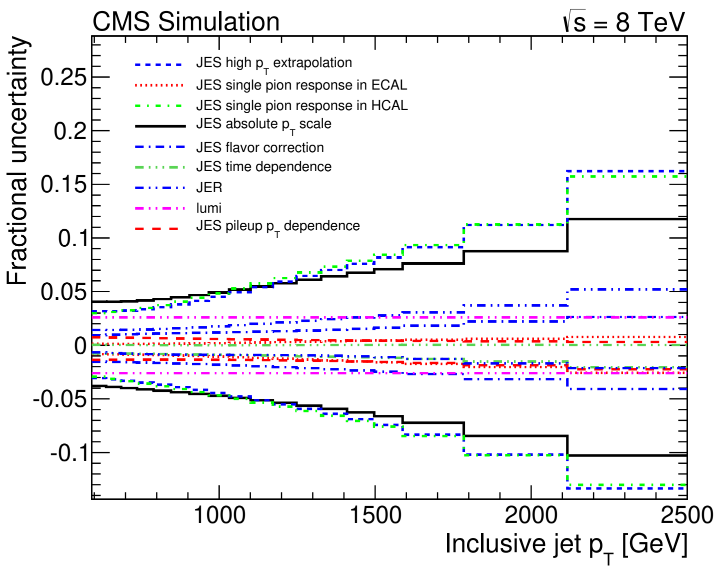

Figure 4: Systematic uncertainty from all experimental sources at ± 1 standard deviation, expressed as a fraction of the central occupancy of each p_T bin. The luminosity uncertainty is constant in jet-p_T, while the JES and JER uncertainties are modelled as transfer matrices between all p_T bins. The seven non-trivial sources of JES uncertainty are shown (out of 19 total).

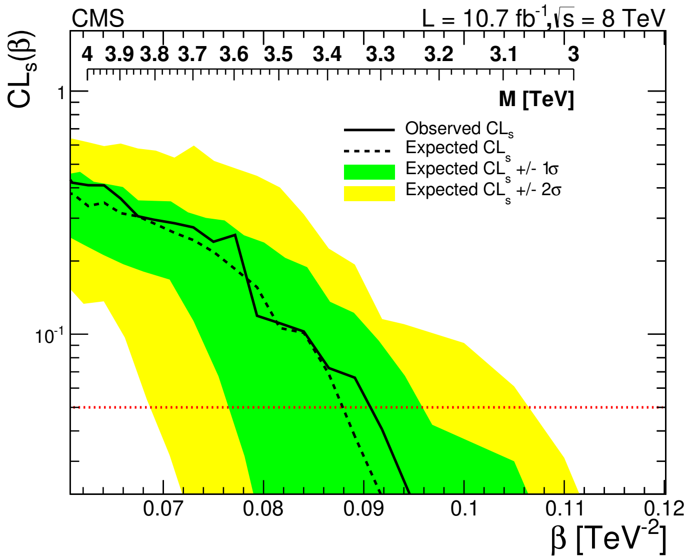

Figure 5: The results of a $\mathrm{CL_s}$ scan in the extinction mass scale, $\beta = M^{-2}$. The observed dependence of $\mathrm{CL_s}$ on β is shown by the solid line. The observed upper limit on β is 0.090 TeV^{-2} at 95% CL (indicated by the horizontal dotted line), corresponding to a lower limit of 3.3 TeV on the extinction mass scale M. The dashed line indicates the expected median of results for the SM hypothesis, while the green (dark) and yellow (light) bands indicate the quantiles, which contain 68% and 95% of the expected results, respectively.

agreement between the observed data and the null hypothesis.

As an additional check, the limit setting procedure is repeated using the MSTW2008 PDF set [39] to derive the SM hypothesis. The limits obtained using the CT10 and MSTW2008 PDFs agree to within 10%. As the MSTW2008 PDFs predict a lower cross section at very high jet-p_{T} compared to CT10, the limit produced in this check is less conservative.

Finally, the limits have been calculated including weak radiative corrections to the SM prediction, with a decrease of less than 100 GeV to the exclusion region.

6 Summary

The first search for the extinction of jet production has been performed at the LHC using proton-proton collision data at $\sqrt{s} = 8$ TeV collected by the CMS detector and corresponding to an integrated luminosity of 10.7 fb^{-1}. The extinction model studied in this analysis is motivated by the search for signatures of terascale gravity at the LHC and assumes the existence of string couplings in the strong-coupling limit. In this limit, the string model predicts suppression of high-p_{T} jet production beyond an extinction mass scale M. A detailed comparison between the measured p_{T} spectrum and the theoretical prediction is conducted. No significant deficit of events is found at high transverse momentum. A 95% confidence level lower limit of 3.3 TeV is set on the extinction mass scale M.

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A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
V. Khachatryan, A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik der OeAW, Wien, Austria
W. Adam, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan[1], M. Friedl, R. Frühwirth[1], V.M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler[1], W. Kiesenhofer, V. Knünz, M. Krammer[1], I. Krätschmer, D. Liko, I. Mikulec, D. Rabady[2], B. Rahbaran, H. Rohringer, R. Schöfbeck, J. Strauss, A. Taurok, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz[1]

National Centre for Particle and High Energy Physics, Minsk, Belarus
V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium
S. Alderweireldt, M. Bansal, S. Bansal, T. Cornelis, E.A. De Wolf, X. Janssen, A. Knutsson, S. Luyckx, S. Ochesanu, B. Roland, R. Rougny, M. Van De Klundert, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

Vrije Universiteit Brussel, Brussel, Belgium
F. Blekman, S. Blyweert, J. D'Hondt, N. Daci, N. Heracleous, A. Kalogeropoulos, J. Keaveney, T.J. Kim, S. Lowette, M. Maes, A. Olbrechts, Q. Python, D. Strom, S. Tavernier, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Villella

Université Libre de Bruxelles, Bruxelles, Belgium
C. Caillol, B. Clerbaux, G. De Lentdecker, D. Dobur, L. Favart, A.P.R. Gay, A. Grebenyuk, A. Léonard, A. Mohammadi, L. Perniè[2], T. Reis, T. Seva, L. Thomas, C. Vander Velde, P. Vanlaer, J. Wang

Ghent University, Ghent, Belgium
V. Adler, K. Beernaert, L. Benucci, A. Cimmino, S. Costantini, S. Crucy, S. Dildick, A. Fagot, G. Garcia, B. Klein, J. Mccartin, A.A. Ocampo Rios, D. Ryckbosch, S. Salva Diblen, M. Sigamani, N. Strobbe, F. Thyssen, M. Tytgat, E. Yazgan, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
S. Basegmez, C. Beluffi[3], G. Bruno, R. Castello, A. Caudron, L. Ceard, G.G. Da Silveira, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco[4], J. Hollar, P. Jez, M. Komm, V. Lemaitre, J. Liao, C. Nuttens, D. Pagano, A. Pin, K. Piotrzkowski, A. Popov[5], L. Quertenmont, M. Selvaggi, M. Vidal Marono, J.M. Vizan Garcia

Université de Mons, Mons, Belgium
N. Beliy, T. Caebergs, E. Daubie, G.H. Hammad

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
G.A. Alves, M. Correa Martins Junior, T. Dos Reis Martins, M.E. Pol

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
W.L. Aldá Júnior, W. Carvalho, J. Chinellato[6], A. Custódio, E.M. Da Costa, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, H. Malbouisson, M. Malek, D. Matos Figueiredo, L. Mundim, H. Nogima, W.L. Prado Da Silva, J. Santaolalla, A. Santoro, A. Sznajder, E.J. Tonelli Manganote[6], A. Vilela Pereira

Universidade Estadual Paulista [a], Universidade Federal do ABC [b], São Paulo, Brazil
C.A. Bernardes[b], F.A. Dias[a,7], T.R. Fernandez Perez Tomei[a], E.M. Gregores[b], P.G. Mercadante[b], S.F. Novaes[a], Sandra S. Padula[a]

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria
A. Aleksandrov, V. Genchev[2], P. Iaydjiev, A. Marinov, S. Piperov, M. Rodozov, G. Sultanov, M. Vutova

University of Sofia, Sofia, Bulgaria
A. Dimitrov, I. Glushkov, R. Hadjiiska, V. Kozhuharov, L. Litov, B. Pavlov, P. Petkov

Institute of High Energy Physics, Beijing, China
J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, R. Du, C.H. Jiang, D. Liang, S. Liang, R. Plestina[8], J. Tao, X. Wang, Z. Wang

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
C. Asawatangtrakuldee, Y. Ban, Y. Guo, Q. Li, W. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, L. Zhang, W. Zou

Universidad de Los Andes, Bogota, Colombia
C. Avila, L.F. Chaparro Sierra, C. Florez, J.P. Gomez, B. Gomez Moreno, J.C. Sanabria

Technical University of Split, Split, Croatia
N. Godinovic, D. Lelas, D. Polic, I. Puljak

University of Split, Split, Croatia
Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, K. Kadija, J. Luetic, D. Mekterovic, L. Sudic

University of Cyprus, Nicosia, Cyprus
A. Attikis, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis

Charles University, Prague, Czech Republic
M. Bodlak, M. Finger, M. Finger Jr.

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
Y. Assran[9], S. Elgammal[10], M.A. Mahmoud[11], A. Radi[10,12]

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
M. Kadastik, M. Murumaa, M. Raidal, A. Tiko

Department of Physics, University of Helsinki, Helsinki, Finland
P. Eerola, G. Fedi, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
J. Härkönen, V. Karimäki, R. Kinnunen, M.J. Kortelainen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, T. Peltola, E. Tuominen, J. Tuominiemi, E. Tuovinen, L. Wendland

Lappeenranta University of Technology, Lappeenranta, Finland
T. Tuuva

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France
M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, C. Favaro, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, J. Malcles, A. Nayak, J. Rander, A. Rosowsky, M. Titov

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
S. Baffioni, F. Beaudette, P. Busson, C. Charlot, T. Dahms, M. Dalchenko, L. Dobrzynski, N. Filipovic, A. Florent, R. Granier de Cassagnac, L. Mastrolorenzo, P. Miné, C. Mironov, I.N. Naranjo, M. Nguyen, C. Ochando, P. Paganini, R. Salerno, J.B. Sauvan, Y. Sirois, C. Veelken, Y. Yilmaz, A. Zabi

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
J.-L. Agram[13], J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, E.C. Chabert, C. Collard, E. Conte[13], J.-C. Fontaine[13], D. Gelé, U. Goerlach, C. Goetzmann, A.-C. Le Bihan, P. Van Hove

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France
S. Gadrat

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
S. Beauceron, N. Beaupere, G. Boudoul[2], S. Brochet, C.A. Carrillo Montoya, J. Chasserat, R. Chierici, D. Contardo[2], P. Depasse, H. El Mamouni, J. Fan, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, T. Kurca, M. Lethuillier, L. Mirabito, S. Perries, J.D. Ruiz Alvarez, D. Sabes, L. Sgandurra, V. Sordini, M. Vander Donckt, P. Verdier, S. Viret, H. Xiao

Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia
Z. Tsamalaidze[14]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
C. Autermann, S. Beranek, M. Bontenackels, B. Calpas, M. Edelhoff, L. Feld, O. Hindrichs, K. Klein, A. Ostapchuk, A. Perieanu, F. Raupach, J. Sammet, S. Schael, D. Sprenger, H. Weber, B. Wittmer, V. Zhukov[5]

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
M. Ata, J. Caudron, E. Dietz-Laursonn, D. Duchardt, M. Erdmann, R. Fischer, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, D. Klingebiel, S. Knutzen, P. Kreuzer, M. Merschmeyer, A. Meyer, M. Olschewski, K. Padeken, P. Papacz, H. Reithler, S.A. Schmitz, L. Sonnenschein, D. Teyssier, S. Thüer, M. Weber

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
V. Cherepanov, Y. Erdogan, G. Flügge, H. Geenen, M. Geisler, W. Haj Ahmad, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, J. Lingemann[2], A. Nowack, I.M. Nugent, L. Perchalla, O. Pooth, A. Stahl

Deutsches Elektronen-Synchrotron, Hamburg, Germany
I. Asin, N. Bartosik, J. Behr, W. Behrenhoff, U. Behrens, A.J. Bell, M. Bergholz[15], A. Bethani, K. Borras, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, S. Choudhury, F. Costanza, C. Diez Pardos, S. Dooling, T. Dorland, G. Eckerlin, D. Eckstein, T. Eichhorn, G. Flucke, J. Garay Garcia, A. Geiser, P. Gunnellini, J. Hauk, G. Hellwig, M. Hempel, D. Horton, H. Jung, M. Kasemann, P. Katsas, J. Kieseler, C. Kleinwort, D. Krücker, W. Lange, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann[15], B. Lutz, R. Mankel, I. Marfin, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Mussgiller, S. Naumann-Emme, O. Novgorodova, F. Nowak, E. Ntomari, H. Perrey, D. Pitzl, R. Placakyte, A. Raspereza, P.M. Ribeiro Cipriano, E. Ron, M.Ö. Sahin, J. Salfeld-Nebgen, P. Saxena, R. Schmidt[15], T. Schoerner-Sadenius, M. Schröder, S. Spannagel, A.D.R. Vargas Trevino, R. Walsh, C. Wissing

University of Hamburg, Hamburg, Germany
M. Aldaya Martin, V. Blobel, M. Centis Vignali, J. Erfle, E. Garutti, K. Goebel, M. Görner, M. Gosselink, J. Haller, R.S. Höing, H. Kirschenmann, R. Klanner, R. Kogler, J. Lange, T. Lapsien, T. Lenz, I. Marchesini, J. Ott, T. Peiffer, N. Pietsch, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Seidel, J. Sibille[16], V. Sola, H. Stadie, G. Steinbrück, D. Troendle, E. Usai, L. Vanelderen

Institut für Experimentelle Kernphysik, Karlsruhe, Germany
C. Barth, C. Baus, J. Berger, C. Böser, E. Butz, T. Chwalek, W. De Boer, A. Descroix, A. Dierlamm, M. Feindt, F. Hartmann[2], T. Hauth[2], U. Husemann, I. Katkov[5], A. Kornmayer[2], E. Kuznetsova, P. Lobelle Pardo, M.U. Mozer, Th. Müller, A. Nürnberg, G. Quast, K. Rabbertz, F. Ratnikov, S. Röcker, H.J. Simonis, F.M. Stober, R. Ulrich, J. Wagner-Kuhr, S. Wayand, T. Weiler, R. Wolf

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
G. Anagnostou, G. Daskalakis, T. Geralis, V.A. Giakoumopoulou, A. Kyriakis, D. Loukas, A. Markou, C. Markou, A. Psallidas, I. Topsis-Giotis

University of Athens, Athens, Greece
L. Gouskos, A. Panagiotou, N. Saoulidou, E. Stiliaris

University of Ioánnina, Ioánnina, Greece
X. Aslanoglou, I. Evangelou, G. Flouris, C. Foudas, P. Kokkas, N. Manthos, I. Papadopoulos, E. Paradas

Wigner Research Centre for Physics, Budapest, Hungary
G. Bencze, C. Hajdu, P. Hidas, D. Horvath[17], F. Sikler, V. Veszpremi, G. Vesztergombi[18], A.J. Zsigmond

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Beni, S. Czellar, J. Karancsi[19], J. Molnar, J. Palinkas, Z. Szillasi

University of Debrecen, Debrecen, Hungary
P. Raics, Z.L. Trocsanyi, B. Ujvari

National Institute of Science Education and Research, Bhubaneswar, India
S.K. Swain

Panjab University, Chandigarh, India
S.B. Beri, V. Bhatnagar, N. Dhingra, R. Gupta, A.K. Kalsi, M. Kaur, M. Mittal, N. Nishu, J.B. Singh

University of Delhi, Delhi, India
Ashok Kumar, Arun Kumar, S. Ahuja, A. Bhardwaj, B.C. Choudhary, A. Kumar, S. Malhotra, M. Naimuddin, K. Ranjan, V. Sharma

Saha Institute of Nuclear Physics, Kolkata, India
S. Banerjee, S. Bhattacharya, K. Chatterjee, S. Dutta, B. Gomber, Sa. Jain, Sh. Jain, R. Khurana, A. Modak, S. Mukherjee, D. Roy, S. Sarkar, M. Sharan

Bhabha Atomic Research Centre, Mumbai, India
A. Abdulsalam, D. Dutta, S. Kailas, V. Kumar, A.K. Mohanty[2], L.M. Pant, P. Shukla, A. Topkar

Tata Institute of Fundamental Research, Mumbai, India
T. Aziz, S. Banerjee, R.M. Chatterjee, R.K. Dewanjee, S. Dugad, S. Ganguly, S. Ghosh,

M. Guchait, A. Gurtu[20], G. Kole, S. Kumar, M. Maity[21], G. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida, K. Sudhakar, N. Wickramage[22]

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
H. Bakhshiansohi, H. Behnamian, S.M. Etesami[23], A. Fahim[24], R. Goldouzian, A. Jafari, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, B. Safarzadeh[25], M. Zeinali

University College Dublin, Dublin, Ireland
M. Felcini, M. Grunewald

INFN Sezione di Bari [a], Università di Bari [b], Politecnico di Bari [c], Bari, Italy
M. Abbrescia[a,b], L. Barbone[a,b], C. Calabria[a,b], S.S. Chhibra[a,b], A. Colaleo[a], D. Creanza[a,c], N. De Filippis[a,c], M. De Palma[a,b], L. Fiore[a], G. Iaselli[a,c], G. Maggi[a,c], M. Maggi[a], S. My[a,c], S. Nuzzo[a,b], A. Pompili[a,b], G. Pugliese[a,c], R. Radogna[a,b,2], G. Selvaggi[a,b], L. Silvestris[a,2], G. Singh[a,b], R. Venditti[a,b], P. Verwilligen[a], G. Zito[a]

INFN Sezione di Bologna [a], Università di Bologna [b], Bologna, Italy
G. Abbiendi[a], A.C. Benvenuti[a], D. Bonacorsi[a,b], S. Braibant-Giacomelli[a,b], L. Brigliadori[a,b], R. Campanini[a,b], P. Capiluppi[a,b], A. Castro[a,b], F.R. Cavallo[a], G. Codispoti[a,b], M. Cuffiani[a,b], G.M. Dallavalle[a], F. Fabbri[a], A. Fanfani[a,b], D. Fasanella[a,b], P. Giacomelli[a], C. Grandi[a], L. Guiducci[a,b], S. Marcellini[a], G. Masetti[a,2], A. Montanari[a], F.L. Navarria[a,b], A. Perrotta[a], F. Primavera[a,b], A.M. Rossi[a,b], T. Rovelli[a,b], G.P. Siroli[a,b], N. Tosi[a,b], R. Travaglini[a,b]

INFN Sezione di Catania [a], Università di Catania [b], CSFNSM [c], Catania, Italy
S. Albergo[a,b], G. Cappello[a], M. Chiorboli[a,b], S. Costa[a,b], F. Giordano[a,c,2], R. Potenza[a,b], A. Tricomi[a,b], C. Tuve[a,b]

INFN Sezione di Firenze [a], Università di Firenze [b], Firenze, Italy
G. Barbagli[a], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], E. Focardi[a,b], E. Gallo[a], S. Gonzi[a,b], V. Gori[a,b,2], P. Lenzi[a,b], M. Meschini[a], S. Paoletti[a], G. Sguazzoni[a], A. Tropiano[a,b]

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, F. Fabbri, D. Piccolo

INFN Sezione di Genova [a], Università di Genova [b], Genova, Italy
F. Ferro[a], M. Lo Vetere[a,b], E. Robutti[a], S. Tosi[a,b]

INFN Sezione di Milano-Bicocca [a], Università di Milano-Bicocca [b], Milano, Italy
M.E. Dinardo[a,b], S. Fiorendi[a,b,2], S. Gennai[a,2], R. Gerosa[2], A. Ghezzi[a,b], P. Govoni[a,b], M.T. Lucchini[a,b,2], S. Malvezzi[a], R.A. Manzoni[a,b], A. Martelli[a,b], B. Marzocchi, D. Menasce[a], L. Moroni[a], M. Paganoni[a,b], D. Pedrini[a], S. Ragazzi[a,b], N. Redaelli[a], T. Tabarelli de Fatis[a,b]

INFN Sezione di Napoli [a], Università di Napoli 'Federico II' [b], Università della Basilicata (Potenza) [c], Università G. Marconi (Roma) [d], Napoli, Italy
S. Buontempo[a], N. Cavallo[a,c], S. Di Guida[a,d,2], F. Fabozzi[a,c], A.O.M. Iorio[a,b], L. Lista[a], S. Meola[a,d,2], M. Merola[a], P. Paolucci[a,2]

INFN Sezione di Padova [a], Università di Padova [b], Università di Trento (Trento) [c], Padova, Italy
P. Azzi[a], N. Bacchetta[a], D. Bisello[a,b], A. Branca[a,b], R. Carlin[a,b], M. Dall'Osso[a,b], T. Dorigo[a], M. Galanti[a,b], F. Gasparini[a,b], P. Giubilato[a,b], A. Gozzelino[a], K. Kanishchev[a,c], S. Lacaprara[a], M. Margoni[a,b], A.T. Meneguzzo[a,b], F. Montecassiano[a], M. Passaseo[a], J. Pazzini[a,b], N. Pozzobon[a,b], P. Ronchese[a,b], F. Simonetto[a,b], E. Torassa[a], M. Tosi[a,b], S. Vanini[a,b], P. Zotto[a,b], A. Zucchetta[a,b], G. Zumerle[a,b]

INFN Sezione di Pavia [a], Università di Pavia [b], Pavia, Italy
M. Gabusi[a,b], S.P. Ratti[a,b], C. Riccardi[a,b], P. Salvini[a], P. Vitulo[a,b]

INFN Sezione di Perugia [a], Università di Perugia [b], Perugia, Italy
M. Biasini[a,b], G.M. Bilei[a], D. Ciangottini[a,b], L. Fanò[a,b], P. Lariccia[a,b], G. Mantovani[a,b], M. Menichelli[a], F. Romeo[a,b], A. Saha[a], A. Santocchia[a,b], A. Spiezia[a,b,2]

INFN Sezione di Pisa [a], Università di Pisa [b], Scuola Normale Superiore di Pisa [c], Pisa, Italy
K. Androsov[a,26], P. Azzurri[a], G. Bagliesi[a], J. Bernardini[a], T. Boccali[a], G. Broccolo[a,c], R. Castaldi[a], M.A. Ciocci[a,26], R. Dell'Orso[a], S. Donato[a,c], F. Fiori[a,c], L. Foà[a,c], A. Giassi[a], M.T. Grippo[a,26], F. Ligabue[a,c], T. Lomtadze[a], L. Martini[a,b], A. Messineo[a,b], C.S. Moon[a,27], F. Palla[a,2], A. Rizzi[a,b], A. Savoy-Navarro[a,28], A.T. Serban[a], P. Spagnolo[a], P. Squillacioti[a,26], R. Tenchini[a], G. Tonelli[a,b], A. Venturi[a], P.G. Verdini[a], C. Vernieri[a,c,2]

INFN Sezione di Roma [a], Università di Roma [b], Roma, Italy
L. Barone[a,b], F. Cavallari[a], D. Del Re[a,b], M. Diemoz[a], M. Grassi[a,b], C. Jorda[a], E. Longo[a,b], F. Margaroli[a,b], P. Meridiani[a], F. Micheli[a,b,2], S. Nourbakhsh[a,b], G. Organtini[a,b], R. Paramatti[a], S. Rahatlou[a,b], C. Rovelli[a], F. Santanastasio[a,b], L. Soffi[a,b,2], P. Traczyk[a,b]

INFN Sezione di Torino [a], Università di Torino [b], Università del Piemonte Orientale (Novara) [c], Torino, Italy
N. Amapane[a,b], R. Arcidiacono[a,c], S. Argiro[a,b,2], M. Arneodo[a,c], R. Bellan[a,b], C. Biino[a], N. Cartiglia[a], S. Casasso[a,b,2], M. Costa[a,b], A. Degano[a,b], N. Demaria[a], L. Finco[a,b], C. Mariotti[a], S. Maselli[a], E. Migliore[a,b], V. Monaco[a,b], M. Musich[a], M.M. Obertino[a,c,2], G. Ortona[a,b], L. Pacher[a,b], N. Pastrone[a], M. Pelliccioni[a], G.L. Pinna Angioni[a,b], A. Potenza[a,b], A. Romero[a,b], M. Ruspa[a,c], R. Sacchi[a,b], A. Solano[a,b], A. Staiano[a], U. Tamponi[a]

INFN Sezione di Trieste [a], Università di Trieste [b], Trieste, Italy
S. Belforte[a], V. Candelise[a,b], M. Casarsa[a], F. Cossutti[a], G. Della Ricca[a,b], B. Gobbo[a], C. La Licata[a,b], M. Marone[a,b], D. Montanino[a,b], A. Schizzi[a,b,2], T. Umer[a,b], A. Zanetti[a]

Kangwon National University, Chunchon, Korea
S. Chang, A. Kropivnitskaya, S.K. Nam

Kyungpook National University, Daegu, Korea
D.H. Kim, G.N. Kim, M.S. Kim, D.J. Kong, S. Lee, Y.D. Oh, H. Park, A. Sakharov, D.C. Son

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
J.Y. Kim, S. Song

Korea University, Seoul, Korea
S. Choi, D. Gyun, B. Hong, M. Jo, H. Kim, Y. Kim, B. Lee, K.S. Lee, S.K. Park, Y. Roh

University of Seoul, Seoul, Korea
M. Choi, J.H. Kim, I.C. Park, S. Park, G. Ryu, M.S. Ryu

Sungkyunkwan University, Suwon, Korea
Y. Choi, Y.K. Choi, J. Goh, E. Kwon, J. Lee, H. Seo, I. Yu

Vilnius University, Vilnius, Lithuania
A. Juodagalvis

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
J.R. Komaragiri

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz[29], R. Lopez-Fernandez, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico
S. Carrillo Moreno, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
I. Pedraza, H.A. Salazar Ibarguen

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
E. Casimiro Linares, A. Morelos Pineda

University of Auckland, Auckland, New Zealand
D. Krofcheck

University of Canterbury, Christchurch, New Zealand
P.H. Butler, S. Reucroft

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, S. Khalid, W.A. Khan, T. Khurshid, M.A. Shah, M. Shoaib

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
G. Brona, K. Bunkowski, M. Cwiok, W. Dominik, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, W. Wolszczak

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
P. Bargassa, C. Beirão Da Cruz E Silva, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, F. Nguyen, J. Rodrigues Antunes, J. Seixas, J. Varela, P. Vischia

Joint Institute for Nuclear Research, Dubna, Russia
S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, V. Karjavin, V. Konoplyanikov, A. Lanev, A. Malakhov, V. Matveev[30], P. Moisenz, V. Palichik, V. Perelygin, M. Savina, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
V. Golovtsov, Y. Ivanov, V. Kim[31], P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev, An. Vorobyev

Institute for Nuclear Research, Moscow, Russia
Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov, A. Toropin

Institute for Theoretical and Experimental Physics, Moscow, Russia
V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, A. Spiridonov, V. Stolin, E. Vlasov, A. Zhokin

P.N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Leonidov, G. Mesyats, S.V. Rusakov, A. Vinogradov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
A. Belyaev, E. Boos, M. Dubinin[7], L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia
I. Azhgirey, I. Bayshev, S. Bitioukov, V. Kachanov, A. Kalinin, D. Konstantinov, V. Krychkine, V. Petrov, R. Ryutin, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
P. Adzic[32], M. Dordevic, M. Ekmedzic, J. Milosevic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
J. Alcaraz Maestre, C. Battilana, E. Calvo, M. Cerrada, M. Chamizo Llatas[2], N. Colino, B. De La Cruz, A. Delgado Peris, D. Domínguez Vázquez, A. Escalante Del Valle, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, G. Merino, E. Navarro De Martino, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, M.S. Soares

Universidad Autónoma de Madrid, Madrid, Spain
C. Albajar, J.F. de Trocóniz, M. Missiroli

Universidad de Oviedo, Oviedo, Spain
H. Brun, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, L. Lloret Iglesias

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, J. Duarte Campderros, M. Fernandez, G. Gomez, A. Graziano, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, J. Piedra Gomez, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A.H. Ball, D. Barney, A. Benaglia, J. Bendavid, L. Benhabib, J.F. Benitez, C. Bernet[8], G. Bianchi, P. Bloch, A. Bocci, A. Bonato, O. Bondu, C. Botta, H. Breuker, T. Camporesi, G. Cerminara, T. Christiansen, S. Colafranceschi[33], M. D'Alfonso, D. d'Enterria, A. Dabrowski, A. David, F. De Guio, A. De Roeck, S. De Visscher, M. Dobson, N. Dupont-Sagorin, A. Elliott-Peisert, J. Eugster, G. Franzoni, W. Funk, M. Giffels, D. Gigi, K. Gill, D. Giordano, M. Girone, F. Glege, R. Guida, S. Gundacker, M. Guthoff, J. Hammer, M. Hansen, P. Harris, J. Hegeman, V. Innocente, P. Janot, K. Kousouris, K. Krajczar, P. Lecoq, C. Lourenço, N. Magini, L. Malgeri, M. Mannelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, S. Morovic, M. Mulders, P. Musella, L. Orsini, L. Pape, E. Perez, L. Perrozzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, M. Pimiä, D. Piparo, M. Plagge, A. Racz, G. Rolandi[34], M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, S. Sekmen, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas[35], D. Spiga, J. Steggemann, B. Stieger, M. Stoye, D. Treille, A. Tsirou, G.I. Veres[18], J.R. Vlimant, N. Wardle, H.K. Wöhri, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
W. Bertl, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, S. König, D. Kotlinski, U. Langenegger, D. Renker, T. Rohe

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland
F. Bachmair, L. Bäni, L. Bianchini, P. Bortignon, M.A. Buchmann, B. Casal, N. Chanon, A. Deisher, G. Dissertori, M. Dittmar, M. Donegà, M. Dünser, P. Eller, C. Grab, D. Hits, W. Lustermann, B. Mangano, A.C. Marini, P. Martinez Ruiz del Arbol, D. Meister, N. Mohr, C. Nägeli[36], P. Nef, F. Nessi-Tedaldi, F. Pandolfi, F. Pauss, M. Peruzzi, M. Quittnat, L. Rebane, F.J. Ronga, M. Rossini, A. Starodumov[37], M. Takahashi, K. Theofilatos, R. Wallny, H.A. Weber

Universität Zürich, Zurich, Switzerland
C. Amsler[38], M.F. Canelli, V. Chiochia, A. De Cosa, A. Hinzmann, T. Hreus, M. Ivova Rikova, B. Kilminster, B. Millan Mejias, J. Ngadiuba, P. Robmann, H. Snoek, S. Taroni, M. Verzetti, Y. Yang

National Central University, Chung-Li, Taiwan
M. Cardaci, K.H. Chen, C. Ferro, C.M. Kuo, W. Lin, Y.J. Lu, R. Volpe, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan
P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, P.H. Chen, C. Dietz, U. Grundler, W.-S. Hou, K.Y. Kao, Y.J. Lei, Y.F. Liu, R.-S. Lu, D. Majumder, E. Petrakou, X. Shi, Y.M. Tzeng, R. Wilken

Chulalongkorn University, Bangkok, Thailand
B. Asavapibhop, N. Srimanobhas, N. Suwonjandee

Cukurova University, Adana, Turkey
A. Adiguzel, M.N. Bakirci[39], S. Cerci[40], C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, E. Gurpinar, I. Hos, E.E. Kangal, A. Kayis Topaksu, G. Onengut[41], K. Ozdemir, S. Ozturk[39], A. Polatoz, K. Sogut[42], D. Sunar Cerci[40], B. Tali[40], H. Topakli[39], M. Vergili

Middle East Technical University, Physics Department, Ankara, Turkey
I.V. Akin, B. Bilin, S. Bilmis, H. Gamsizkan, G. Karapinar[43], K. Ocalan, U.E. Surat, M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey
E. Gülmez, B. Isildak[44], M. Kaya[45], O. Kaya[45]

Istanbul Technical University, Istanbul, Turkey
H. Bahtiyar[46], E. Barlas, K. Cankocak, F.I. Vardarlı, M. Yücel

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
L. Levchuk, P. Sorokin

University of Bristol, Bristol, United Kingdom
J.J. Brooke, E. Clement, D. Cussans, H. Flacher, R. Frazier, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, Z. Meng, D.M. Newbold[47], S. Paramesvaran, A. Poll, S. Senkin, V.J. Smith, T. Williams

Rutherford Appleton Laboratory, Didcot, United Kingdom
K.W. Bell, A. Belyaev[48], C. Brew, R.M. Brown, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, W.J. Womersley, S.D. Worm

Imperial College, London, United Kingdom
M. Baber, R. Bainbridge, O. Buchmuller, D. Burton, D. Colling, N. Cripps, M. Cutajar, P. Dauncey, G. Davies, M. Della Negra, P. Dunne, W. Ferguson, J. Fulcher, D. Futyan, A. Gilbert,

G. Hall, G. Iles, M. Jarvis, G. Karapostoli, M. Kenzie, R. Lane, R. Lucas[47], L. Lyons, A.-M. Magnan, S. Malik, J. Marrouche, B. Mathias, J. Nash, A. Nikitenko[37], J. Pela, M. Pesaresi, K. Petridis, D.M. Raymond, S. Rogerson, A. Rose, C. Seez, P. Sharp[†], A. Tapper, M. Vazquez Acosta, T. Virdee

Brunel University, Uxbridge, United Kingdom
J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, D. Leggat, D. Leslie, W. Martin, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner

Baylor University, Waco, USA
J. Dittmann, K. Hatakeyama, A. Kasmi, H. Liu, T. Scarborough

The University of Alabama, Tuscaloosa, USA
O. Charaf, S.I. Cooper, C. Henderson, P. Rumerio

Boston University, Boston, USA
A. Avetisyan, T. Bose, C. Fantasia, A. Heister, P. Lawson, C. Richardson, J. Rohlf, D. Sperka, J. St. John, L. Sulak

Brown University, Providence, USA
J. Alimena, S. Bhattacharya, G. Christopher, D. Cutts, Z. Demiragli, A. Ferapontov, A. Garabedian, U. Heintz, S. Jabeen, G. Kukartsev, E. Laird, G. Landsberg, M. Luk, M. Narain, M. Segala, T. Sinthuprasith, T. Speer, J. Swanson

University of California, Davis, Davis, USA
R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, M. Gardner, W. Ko, R. Lander, T. Miceli, M. Mulhearn, D. Pellett, J. Pilot, F. Ricci-Tam, M. Searle, S. Shalhout, J. Smith, M. Squires, D. Stolp, M. Tripathi, S. Wilbur, R. Yohay

University of California, Los Angeles, USA
R. Cousins, P. Everaerts, C. Farrell, J. Hauser, M. Ignatenko, G. Rakness, E. Takasugi, V. Valuev, M. Weber

University of California, Riverside, Riverside, USA
J. Babb, R. Clare, J. Ellison, J.W. Gary, G. Hanson, J. Heilman, P. Jandir, E. Kennedy, F. Lacroix, H. Liu, O.R. Long, A. Luthra, M. Malberti, H. Nguyen, A. Shrinivas, J. Sturdy, S. Sumowidagdo, S. Wimpenny

University of California, San Diego, La Jolla, USA
W. Andrews, J.G. Branson, G.B. Cerati, S. Cittolin, R.T. D'Agnolo, D. Evans, A. Holzner, R. Kelley, M. Lebourgeois, J. Letts, I. Macneill, D. Olivito, S. Padhi, C. Palmer, M. Pieri, M. Sani, V. Sharma, S. Simon, E. Sudano, M. Tadel, Y. Tu, A. Vartak, F. Würthwein, A. Yagil, J. Yoo

University of California, Santa Barbara, Santa Barbara, USA
D. Barge, J. Bradmiller-Feld, C. Campagnari, T. Danielson, A. Dishaw, K. Flowers, M. Franco Sevilla, P. Geffert, C. George, F. Golf, J. Incandela, C. Justus, N. Mccoll, J. Richman, D. Stuart, W. To, C. West

California Institute of Technology, Pasadena, USA
A. Apresyan, A. Bornheim, J. Bunn, Y. Chen, E. Di Marco, J. Duarte, A. Mott, H.B. Newman, C. Pena, C. Rogan, M. Spiropulu, V. Timciuc, R. Wilkinson, S. Xie, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA
V. Azzolini, A. Calamba, R. Carroll, T. Ferguson, Y. Iiyama, M. Paulini, J. Russ, H. Vogel, I. Vorobiev

University of Colorado at Boulder, Boulder, USA
J.P. Cumalat, B.R. Drell, W.T. Ford, A. Gaz, E. Luiggi Lopez, U. Nauenberg, J.G. Smith, K. Stenson, K.A. Ulmer, S.R. Wagner

Cornell University, Ithaca, USA
J. Alexander, A. Chatterjee, J. Chu, S. Dittmer, N. Eggert, W. Hopkins, B. Kreis, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Ryd, E. Salvati, L. Skinnari, W. Sun, W.D. Teo, J. Thom, J. Thompson, J. Tucker, Y. Weng, L. Winstrom, P. Wittich

Fairfield University, Fairfield, USA
D. Winn

Fermi National Accelerator Laboratory, Batavia, USA
S. Abdullin, M. Albrow, J. Anderson, G. Apollinari, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, H.W.K. Cheung, F. Chlebana, S. Cihangir, V.D. Elvira, I. Fisk, J. Freeman, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, D. Hare, R.M. Harris, J. Hirschauer, B. Hooberman, S. Jindariani, M. Johnson, U. Joshi, K. Kaadze, B. Klima, S. Kwan, J. Linacre, D. Lincoln, R. Lipton, T. Liu, J. Lykken, K. Maeshima, J.M. Marraffino, V.I. Martinez Outschoorn, S. Maruyama, D. Mason, P. McBride, K. Mishra, S. Mrenna, Y. Musienko[30], S. Nahn, C. Newman-Holmes, V. O'Dell, O. Prokofyev, E. Sexton-Kennedy, S. Sharma, A. Soha, W.J. Spalding, L. Spiegel, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, R. Vidal, A. Whitbeck, J. Whitmore, F. Yang

University of Florida, Gainesville, USA
D. Acosta, P. Avery, D. Bourilkov, M. Carver, T. Cheng, D. Curry, S. Das, M. De Gruttola, G.P. Di Giovanni, R.D. Field, M. Fisher, I.K. Furic, J. Hugon, J. Konigsberg, A. Korytov, T. Kypreos, J.F. Low, K. Matchev, P. Milenovic[49], G. Mitselmakher, L. Muniz, A. Rinkevicius, L. Shchutska, N. Skhirtladze, M. Snowball, J. Yelton, M. Zakaria

Florida International University, Miami, USA
V. Gaultney, S. Hewamanage, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida State University, Tallahassee, USA
T. Adams, A. Askew, J. Bochenek, B. Diamond, J. Haas, S. Hagopian, V. Hagopian, K.F. Johnson, H. Prosper, V. Veeraraghavan, M. Weinberg

Florida Institute of Technology, Melbourne, USA
M.M. Baarmand, M. Hohlmann, H. Kalakhety, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, USA
M.R. Adams, L. Apanasevich, V.E. Bazterra, D. Berry, R.R. Betts, I. Bucinskaite, R. Cavanaugh, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, S. Khalatyan, P. Kurt, D.H. Moon, C. O'Brien, C. Silkworth, P. Turner, N. Varelas

The University of Iowa, Iowa City, USA
E.A. Albayrak[46], B. Bilki[50], W. Clarida, K. Dilsiz, F. Duru, M. Haytmyradov, J.-P. Merlo, H. Mermerkaya[51], A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok[46], A. Penzo, R. Rahmat, S. Sen, P. Tan, E. Tiras, J. Wetzel, T. Yetkin[52], K. Yi

Johns Hopkins University, Baltimore, USA
B.A. Barnett, B. Blumenfeld, S. Bolognesi, D. Fehling, A.V. Gritsan, P. Maksimovic, C. Martin, M. Swartz

The University of Kansas, Lawrence, USA
P. Baringer, A. Bean, G. Benelli, C. Bruner, J. Gray, R.P. Kenny III, M. Murray, D. Noonan, S. Sanders, J. Sekaric, R. Stringer, Q. Wang, J.S. Wood

Kansas State University, Manhattan, USA
A.F. Barfuss, I. Chakaberia, A. Ivanov, S. Khalil, M. Makouski, Y. Maravin, L.K. Saini, S. Shrestha, I. Svintradze

Lawrence Livermore National Laboratory, Livermore, USA
J. Gronberg, D. Lange, F. Rebassoo, D. Wright

University of Maryland, College Park, USA
A. Baden, B. Calvert, S.C. Eno, J.A. Gomez, N.J. Hadley, R.G. Kellogg, T. Kolberg, Y. Lu, M. Marionneau, A.C. Mignerey, K. Pedro, A. Skuja, M.B. Tonjes, S.C. Tonwar

Massachusetts Institute of Technology, Cambridge, USA
A. Apyan, R. Barbieri, G. Bauer, W. Busza, I.A. Cali, M. Chan, L. Di Matteo, V. Dutta, G. Gomez Ceballos, M. Goncharov, D. Gulhan, M. Klute, Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, T. Ma, C. Paus, D. Ralph, C. Roland, G. Roland, G.S.F. Stephans, F. Stöckli, K. Sumorok, D. Velicanu, J. Veverka, B. Wyslouch, M. Yang, M. Zanetti, V. Zhukova

University of Minnesota, Minneapolis, USA
B. Dahmes, A. De Benedetti, A. Gude, S.C. Kao, K. Klapoetke, Y. Kubota, J. Mans, N. Pastika, R. Rusack, A. Singovsky, N. Tambe, J. Turkewitz

University of Mississippi, Oxford, USA
J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, USA
E. Avdeeva, K. Bloom, S. Bose, D.R. Claes, A. Dominguez, R. Gonzalez Suarez, J. Keller, D. Knowlton, I. Kravchenko, J. Lazo-Flores, S. Malik, F. Meier, G.R. Snow

State University of New York at Buffalo, Buffalo, USA
J. Dolen, A. Godshalk, I. Iashvili, A. Kharchilava, A. Kumar, S. Rappoccio

Northeastern University, Boston, USA
G. Alverson, E. Barberis, D. Baumgartel, M. Chasco, J. Haley, A. Massironi, D.M. Morse, D. Nash, T. Orimoto, D. Trocino, D. Wood, J. Zhang

Northwestern University, Evanston, USA
K.A. Hahn, A. Kubik, N. Mucia, N. Odell, B. Pollack, A. Pozdnyakov, M. Schmitt, S. Stoynev, K. Sung, M. Velasco, S. Won

University of Notre Dame, Notre Dame, USA
A. Brinkerhoff, K.M. Chan, A. Drozdetskiy, M. Hildreth, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, W. Luo, S. Lynch, N. Marinelli, T. Pearson, M. Planer, R. Ruchti, N. Valls, M. Wayne, M. Wolf, A. Woodard

The Ohio State University, Columbus, USA
L. Antonelli, J. Brinson, B. Bylsma, L.S. Durkin, S. Flowers, C. Hill, R. Hughes, K. Kotov, T.Y. Ling, D. Puigh, M. Rodenburg, G. Smith, C. Vuosalo, B.L. Winer, H. Wolfe, H.W. Wulsin

Princeton University, Princeton, USA
E. Berry, O. Driga, P. Elmer, P. Hebda, A. Hunt, S.A. Koay, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Piroué, X. Quan, H. Saka, D. Stickland[2], C. Tully, J.S. Werner, S.C. Zenz, A. Zuranski

University of Puerto Rico, Mayaguez, USA
E. Brownson, H. Mendez, J.E. Ramirez Vargas

Purdue University, West Lafayette, USA
E. Alagoz, V.E. Barnes, D. Benedetti, G. Bolla, D. Bortoletto, M. De Mattia, A. Everett, Z. Hu, M.K. Jha, M. Jones, K. Jung, M. Kress, N. Leonardo, D. Lopes Pegna, V. Maroussov, P. Merkel, D.H. Miller, N. Neumeister, B.C. Radburn-Smith, I. Shipsey, D. Silvers, A. Svyatkovskiy, F. Wang, W. Xie, L. Xu, H.D. Yoo, J. Zablocki, Y. Zheng

Purdue University Calumet, Hammond, USA
N. Parashar, J. Stupak

Rice University, Houston, USA
A. Adair, B. Akgun, K.M. Ecklund, F.J.M. Geurts, W. Li, B. Michlin, B.P. Padley, R. Redjimi, J. Roberts, J. Zabel

University of Rochester, Rochester, USA
B. Betchart, A. Bodek, R. Covarelli, P. de Barbaro, R. Demina, Y. Eshaq, T. Ferbel, A. Garcia-Bellido, P. Goldenzweig, J. Han, A. Harel, A. Khukhunaishvili, D.C. Miner, G. Petrillo, D. Vishnevskiy

The Rockefeller University, New York, USA
R. Ciesielski, L. Demortier, K. Goulianos, G. Lungu, C. Mesropian

Rutgers, The State University of New Jersey, Piscataway, USA
S. Arora, A. Barker, J.P. Chou, C. Contreras-Campana, E. Contreras-Campana, D. Duggan, D. Ferencek, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, A. Lath, S. Panwalkar, M. Park, R. Patel, V. Rekovic, S. Salur, S. Schnetzer, C. Seitz, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

University of Tennessee, Knoxville, USA
K. Rose, S. Spanier, A. York

Texas A&M University, College Station, USA
O. Bouhali[53], R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon[54], V. Khotilovich, V. Krutelyov, R. Montalvo, I. Osipenkov, Y. Pakhotin, A. Perloff, J. Roe, A. Rose, A. Safonov, T. Sakuma, I. Suarez, A. Tatarinov

Texas Tech University, Lubbock, USA
N. Akchurin, C. Cowden, J. Damgov, C. Dragoiu, P.R. Dudero, J. Faulkner, K. Kovitanggoon, S. Kunori, S.W. Lee, T. Libeiro, I. Volobouev

Vanderbilt University, Nashville, USA
E. Appelt, A.G. Delannoy, S. Greene, A. Gurrola, W. Johns, C. Maguire, Y. Mao, A. Melo, M. Sharma, P. Sheldon, B. Snook, S. Tuo, J. Velkovska

University of Virginia, Charlottesville, USA
M.W. Arenton, S. Boutle, B. Cox, B. Francis, J. Goodell, R. Hirosky, A. Ledovskoy, H. Li, C. Lin, C. Neu, J. Wood

Wayne State University, Detroit, USA
S. Gollapinni, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane

University of Wisconsin, Madison, USA
D.A. Belknap, D. Carlsmith, M. Cepeda, S. Dasu, S. Duric, E. Friis, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbers, J. Klukas, A. Lanaro, C. Lazaridis, A. Levine, R. Loveless, A. Mohapatra, I. Ojalvo, T. Perry, G.A. Pierro, G. Polese, I. Ross, T. Sarangi, A. Savin, W.H. Smith, N. Woods

†: Deceased
1: Also at Vienna University of Technology, Vienna, Austria
2: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
3: Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
4: Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
5: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
6: Also at Universidade Estadual de Campinas, Campinas, Brazil
7: Also at California Institute of Technology, Pasadena, USA
8: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
9: Also at Suez University, Suez, Egypt
10: Also at British University in Egypt, Cairo, Egypt
11: Also at Fayoum University, El-Fayoum, Egypt
12: Now at Ain Shams University, Cairo, Egypt
13: Also at Université de Haute Alsace, Mulhouse, France
14: Also at Joint Institute for Nuclear Research, Dubna, Russia
15: Also at Brandenburg University of Technology, Cottbus, Germany
16: Also at The University of Kansas, Lawrence, USA
17: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
18: Also at Eötvös Loránd University, Budapest, Hungary
19: Also at University of Debrecen, Debrecen, Hungary
20: Now at King Abdulaziz University, Jeddah, Saudi Arabia
21: Also at University of Visva-Bharati, Santiniketan, India
22: Also at University of Ruhuna, Matara, Sri Lanka
23: Also at Isfahan University of Technology, Isfahan, Iran
24: Also at Sharif University of Technology, Tehran, Iran
25: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
26: Also at Università degli Studi di Siena, Siena, Italy
27: Also at Centre National de la Recherche Scientifique (CNRS) - IN2P3, Paris, France
28: Also at Purdue University, West Lafayette, USA
29: Also at Universidad Michoacana de San Nicolas de Hidalgo, Morelia, Mexico
30: Also at Institute for Nuclear Research, Moscow, Russia
31: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
32: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
33: Also at Facoltà Ingegneria, Università di Roma, Roma, Italy
34: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
35: Also at University of Athens, Athens, Greece
36: Also at Paul Scherrer Institut, Villigen, Switzerland
37: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
38: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland

39: Also at Gaziosmanpasa University, Tokat, Turkey
40: Also at Adiyaman University, Adiyaman, Turkey
41: Also at Cag University, Mersin, Turkey
42: Also at Mersin University, Mersin, Turkey
43: Also at Izmir Institute of Technology, Izmir, Turkey
44: Also at Ozyegin University, Istanbul, Turkey
45: Also at Kafkas University, Kars, Turkey
46: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
47: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
48: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
49: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
50: Also at Argonne National Laboratory, Argonne, USA
51: Also at Erzincan University, Erzincan, Turkey
52: Also at Yildiz Technical University, Istanbul, Turkey
53: Also at Texas A&M University at Qatar, Doha, Qatar
54: Also at Kyungpook National University, Daegu, Korea